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Performance enhancements in powder-mixed near-dry electric discharge machining

Sanjay Sundriyal[a], Vipin[a] & RS Walia[b]*

[a] Department of Mechanical Engineering, Delhi Technological University, Delhi 110 042, India
[b] Department of Production and Industrial Engineering, Punjab Engineering College, Chandigarh, 160 012, India

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Powder-mixed near-dry electric discharge machining (PMND-EDM) process have been attracting attention in the manufacturing community because of its capability to produce the end products with better surface quality characteristics and improved machining rate. Present work is an effort to understand the influence of process variables like tool diameter, flow rate of dielectric mist, concentration of metallic powder and mist pressure of dielectric medium. Taguchi method orthogonal array L9 was used for the conduction of experiments. Analysis of variance (ANOVA) was employed to find out the significance of process parameters. The results reveal that the optimum process parameters for the experimental condition for maximum MRR (0.11 mg s^{-1})was at tool diameter at A1 (2mm), flow rate of mist at B3 (15 ml min^{-1}), concentration of metallic powder at C3 (25 gm l^{-1}) and mist pressure of dielectric at D3 (0.6 MPa). It has been also concluded that metallic powder was responsible for surface modification to achieve higher micro-hardness value up to 530.10 Vickers hardness number along with refined surface characteristics.

Keywords: Material removal rate, Powder-mixed near-dry EDM, Micro-hardness

1 Introduction

The necessity of machines using the least harmful cutting fluids has prompted many researchers to investigate the use of minimum quantity lubrication (MQL) in near-dry machining (NDM). In NDM, machining has been done with the supply of minute quantities of lubricant or mist at the work surface. It was developed as an alternative technique to supply the internal high-pressure coolant, reducing the use of metal-working fluids (MWFs), which eventually also led to a reduction in the cost of MWFs. In NDM, the cooling medium was a combination of air and oil in the form of an aerosol or minute droplets of mist. The process feasibility of near-dry electrical discharge machining (NDEDM) was explored in 1981, and further investigations were performed on dielectric mixtures of mist with gases such as argon and nitrogen[1]. In powder-mixed EDM (PM-EDM), the effect on the breakdown voltage of kerosene by the addition of graphite powder was studied and it was noted that some powders, such as graphite and silicon when mixed with dielectric, improves the distribution of spark at the discharge gap leading to the creation of very fine glossy surfaces[2-3]. The material removal rate (MRR) increases with the proper addition of metallic powders to the dielectric fluid. An approach was made to achieve optimal process parameters setting in PM-EDM, and the study revealed that process parameters at optimum levels in PM-EDM gave higher MRR and surface finish (Ra)[4]. The effect of different powder concentration of graphite powder on MRR in H-11 die steel was studied, revealing that the addition of graphite powder at a concentration of 6g/l enhances the MRR and Ra[5]. The research was also conducted with different dielectrics on environmental and hazard and operability (HAZOP) analysis in PM-EDM, concluding that HAZOP analysis successfully reduced the wastage of dielectric, and minimized the machining cost and environmental hazards as compared to traditional EDM machining methods[6]. The thermal phenomenon in powder-mixed near-dry electrical discharge machining (PMND-EDM) was explained, and the tendency of variation in MRR was analyzed by varying each process parameter[7-9]. The plasma channel characteristics in PM-EDM were analyzed and it was proved that the plasma channel was much more stable in PM-EDM than the plasma formed in pure kerosene oil because the plasma

*Corresponding author (E mail: waliaravinder@yahoo.com)

generated in PM-EDM was compressed by the electric bridge of conductive powder particles in EDM oil[10]. Parametric study improved the machinability of titanium alloy (Ti–6Al–4V)[11]. It has been observed by the research study that a high suspended particle concentration in dielectric liquid enhance the material transfer mechanism in a particulate form[12]. Another study revealed that flushing mode of the dielectric medium plays an important role in any EDM operation. Incorrect flushing can result in erratic cutting and poor machining conditions[13]. It was observed that powder additives in dielectric medium enhance MRR, surface finish while residual stress in the machined samples was reduced considerably along with reduced tool wear rate[14-17].

The surface finish on the machined samples in PM-EDM was increased by 60% by the addition of aluminium powder in the dielectric medium which improved heat distribution effect at the inter-electrode gap[18]. A very crucial role was played by the metallic powder particle size in determining the surface finish of the machined sample in PM-EDM. It was also suggested that small particle size (70–80 nm) generates higher surface finish[19]. Also at 6 g/l metallic powder concentration, there was a tremendous improvement in the surface texture of components due to reduced micro-cracks and recast layer[20]. It was revealed that the powder additives improved the overall morphology of the workpiece (Inconel 718) along with increased MRR[21].

Several studies have also been done regarding enhancing the micro-hardness (MH) value and surface roughness of the machined components by powder-additive EDM methodology. The Taguchi method was followed to obtain a combination of process variables for achieving the best MH of EN-31 workpiece by using copper-tungsten tool in the electrical discharge alloying (EDA) process[22]. It was also reported that carbides generated on the machined surface increased the hardness as high as 912 HV without much sacrifice of the roughness of the machined surface[23]. The surfaces of the die steel materials were modified by the addition of tungsten powder in a dielectric medium in the EDM process and resulted in 100% increase in MH value[24]. The MH of cryogenically treated aluminium alloy was improved by 94.85% in PM-EDM[25]. A Taguchi L9 orthogonal array was utilized to increase the MH of the workpiece in PMND-EDM and resulted in an increase of MH up to 506.63 Vickers hardness number (HV)[26]. Investigations were also performed in the field of wire EDM and further, the analysis of SEM pictures gave important data about the character of wire tool wear during processing[27]. There were representations of the assets, which were developed for vibroacoustic diagnostics of EDM to reduce the negative effects of the technology on the machined products[28]. Various studies have shown that now there is paradigm shift from EDM to PM-EDM because of better machining results and quality products[29].

Sufficient efforts are needed to be undertaken for the improvement of Near Dry EDM process efficiency/productivity in terms of more material removal rate and surface Quality. More efforts needed for the optimization of process parameters from the component quality point of view. There are confliction opinions from the various researchers regarding the effect of some of the variables on the response parameters. Still there is need to develop EDM which is environmental friendly and has higher material removal rate. Limitation of the traditional process to correct the form geometry is not possible with the existing processes, requiring the development of new processes, therefore there was need of experimental study for the effect of various process parameters on performance characteristics and to develop the empirical relationships between important process parameters and response characteristics as shown in Fig. 1.

2 Materials and Methods

The developed setup for PMND-EDM is shown in Fig. 2 while the enlarged view is shown in Fig. 3. PMND-EDM works on the principle of conversion of electric energy to heat energy which is used to machine hard conductive materials. The conductive powder additives along with the dielectric medium supplied at the machining gap enhance the thermal conductivity by bridging effect which increases the intensity of the plasma to a much higher value thereby also enhancing the material removal rate[29-30]. The pressurized dielectric mist further enhances the surface finish over the machined sample by flushing the debris away in a better manner during pulse- off time or flushing phase or after discharge phase of sparks gets over[31].

Table 1 shows the experimental condition, the workpiece selected for machining was EN-31 while

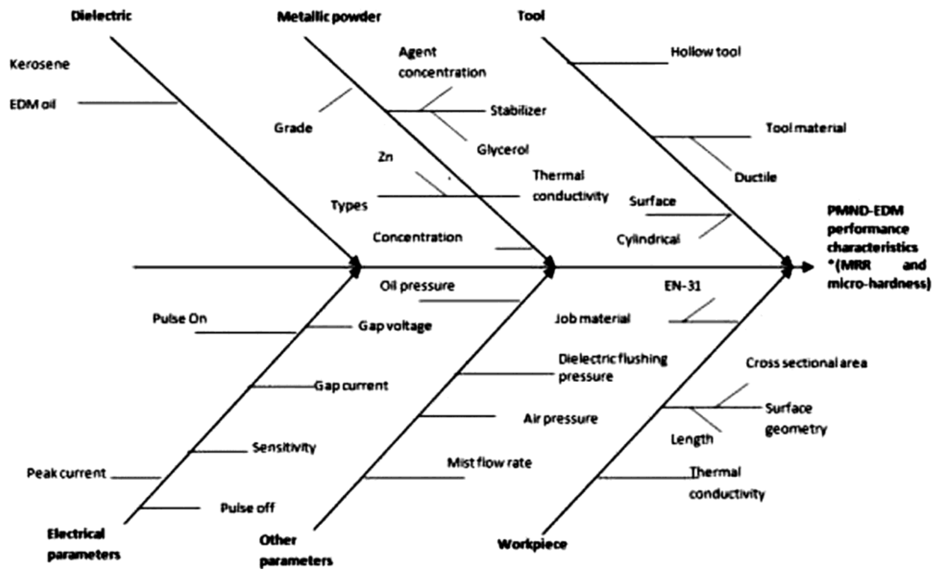

Fig. 1 — Cause and effect diagram for PMND-EDM.

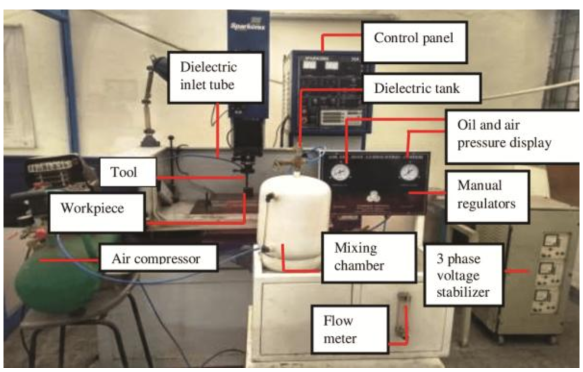

Fig. 2 —Indigenously developed setup for PMND-EDM.

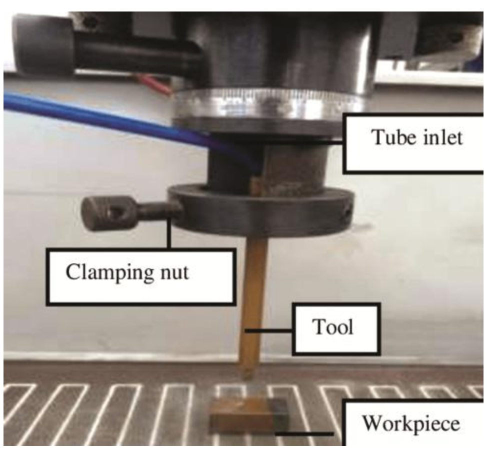

Fig. 3 — Enlarged view of Tool setup for PMND-EDM.

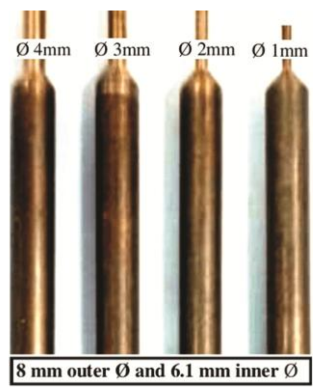

Fig. 4 — Developed copper tool electrodes for experiments (All dimensions are in mm).

the tool electrode material (copper) with different dimensions isshown in Fig. 4. The dielectric medium or mist was a mixture of EDM oil (LL-221), compressed air, metallic powder (zinc), and 5% glycerol serving as a stabilizing agent[32-33]. The role of glycerol was to prevent the metallic powders from settling down in the tank and also maintaining the mixture homogeneity. The pulse-on (*Pon)* and pulse-off (*Poff*) were 600 µs and 90 µs respectively. The metallic powder (zinc) was selected due to continuous research in the field of PMND-EDM and due to thethefavourable results obtained in previously published work.

The output response for the study was the material removal rate while micro-hardness analysis was also carried out for the machined samples. Series of experiments were performed as per Taguchi L9 (OA) for material removal rate (MRR). Each series of experiments was performed in three runs and a total of 27 experiments each were performed for analysis of MRR respectively.

Signal to Noise ratio (S/N) is a technique of measurement in science and engineering to analyze

Table 1 — Experimental conditions of selected process parameters

Symbol	Process parameters	Unit	Level 1	Level 2	Level 3
A	Tool diameter	mm	2	3	4
B	Mist flow rate	ml min^{-1}	5	10	15
C	Metallic powder concentration	g l^{-1}	15	20	25
D	Mist Pressure	MPa	0.4	0.5	0.6

*Values of other constant parameters: Machining time 10 min; P_{on} 600 µs; P_{off} 90 µs; Discharge current 12A; Gap volateg 30 V; Tool electrode Copper; Workpiece EN-31, Metallic zinc powder, stabilizing agent – 5% glycerol, EN-31 with dimensions (40 mm x 25 mm x 25 mm)

the effect on output response relative to the target or nominal value under different noise condition, (dB). In this study, the goal for experimentation is to measure MRR under the noise of different conditions that are involved during experimentations.

The signal to noise quality characteristic of MRR is considered higher the better for which the expression is given in Eq. 1[26]:

$$S/N\ ratio = -log_{10}(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_{ij}^2}) \quad \ldots (1)$$

where,

n = Number of replications
y_{ij} = observed response value

While material removal rate experimentally was calculated by Eq. (2)

$$MRR = (W_i - W_f)/T_m \quad \ldots (2)$$

where,

MRR is material removal rate (mg/s)
T_m= time taken for machining (seconds)
W_i= initial weight of workpiece sample
W_f= final weight of workpiece after machining

The weight of the specimen was measured using the electronic balance of least count 0.001 gm (Asia Techno weigh India). Optical profilometer (ZeGage model TM3000, made in the USA) was utilized for measurement of the machined surface profile while the micro-hardness testing was performed with the help of Fischerscope instrument (HM2000S model, USA).

2.1 Performance characteristics estimation for MRR

Response characteristic MRR can be determined by using Eq. 3[26]as:

$$MRR = \overline{A_1} + \overline{B_3} + \overline{C_3} + \overline{D_3} - 3\overline{MRR} \quad \ldots (3)$$

The estimation of the computed value of the observed data (i.e. MRR) is measured by the confidence interval. It gives the range of the value for the mean with a confidence level of 95%. This means, that the observed value (population) lies within the proposed range with 95% confidence. The confidence interval at 95% of confirmation experiments *(CI_{CE})* can be determined by Eq. 4 while the confidence interval at 95% of the population *(CI_{POP})*can be determined by Eq. 5[17].

$$CI_{CE} = \sqrt{F_{\alpha}(1, f_e)V_e\left[\frac{1}{n_{eff}} + \frac{1}{R}\right]} \quad \ldots (4)$$

$$CI_{pop} = \sqrt{F\alpha\ (1, fe)\ Ve\ /\ n_{eff}} \quad \ldots (5)$$

where, $F = \frac{variation\ between\ sample\ means}{variation\ within\ the\ samples}$

N= total number of experiments; R= sample size for confirmation experiments); V_e= error variance; f_e = error DOF; F = cirtical ratio, *CI pop* =Confidence interwal of population; *CIce*= Confidence interwal of confirmation experiments

So, MRR = 0.357 (mg s^{-1}), CI_{CE} = ± 0.0397, CI_{POP} = ± 0.0198

The predicted optimal range of confidence interval of confirmation experiments *(CI_{CE})* is:

Mean MRR − CI_{CE} <MRR (mg/s)<Mean MRR + CI_{CE}

i.e. 0.356 (mg s^{-1}) < MRR (mg s^{-1}) < 0.359 (mg s^{-1})

The 95% confirmation interval of the predicted mean is:

Mean MRR− CI_{POP} <MRR (mg s^{-1})<Mean MRR+ CI_{POP}

i.e.0.337 (mg s^{-1}) < MRR (mg s^{-1}) < 0.377 (mg s^{-1})

2.2 Confirmation experiments for MRR

Three repetitions of confirmation experiments for MRR were performed for process parameters at optimized levels. The confirmation test for MRR was performed at the experimental condition ofA1,B3,C3, and D3. The experimental material removal rate for three runs at optimized conditions was found to be 0.344 mg s^{-1}, 0.339 mg s^{-1}, and 0.356 mg s^{-1} respectively.The mean experimental MRR calculated at the optimized process of parameters was 0.346 mg s^{-1} which was within the confidence interval of predicted MRR. The confirmation tests were performed thrice for the average value of MRR at optimum process parameters. The experimental MRR obtained were

0.344, 0.339, and 0.356 mg/s at input process parameters at A1, B3, C3, D3. The average value for MRR was 0.346 mg/s, and thus it was proven that the predicted value of MRR lies in the optimum range.

3 Results and Discussion

3.1 Analysis for MRR

Firstly in this section, a comparison was made on the effect of different process parameters on the workpiece based on ANOVA analysis. The effect of parameters at different levels was discussed subsequently. The parametric investigation was performed to get an insight into the performance characteristics. The discussion further refers to surface properties such as surface finish and micro-hardness. Finally, the EDAX mapping was performed for the chemical composition of the machined samples.

The experiments were performed as per Taguchi L9(OA). The experiments were conducted for analysis of MRR. Each series of experiments was run for three trials and the results obtained are shown in Table 2.

The EN-31 workpieces were machined as per experimental condition and it was observed that phase transformation due to sublimation and solidification resulted in the formation of a re-solidified layer around the groove cut over the workpiece machined surface as shown in Fig. 5. Optical profilometer was utilized for measurement of machined surface profile and the maximum surface finish was found to be 1.1µm as shown in Fig. 6.

The MRR was increased due to the higher discharge energy in PMND-EDM which led to the sublimation of more material in the eroded puddle of the machined sample. The average values and main effects values of MRR were calculated at different levels which were L1, L2 and L3 while the S/N ratio and raw data values at different levels of parameters are shown in Table 3. Pooled ANOVA (analysis of variance) for MRR at confidence level (95 %) is shown in Table 4. The tabulated value for F-ratio was 3.55 for raw data while the tabulated F-ratio value for S/N was 19.

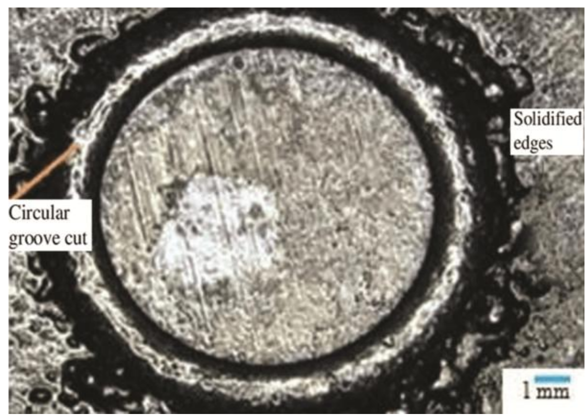

Fig. 5 —*Machined EN-31 workpieces by PMND-EDM as per Taguchi L_9 (OA).*

Table 2 — Experimental Results of Residual stress and Material Removal Rate as per Taguchi L_9 OA

Exp. No	Parameter trial condition				MRR (mg s^{-1})			S/N (dB)
	A	B	C	D	R1	R2	R3	
1	2	5	15	0.4	0.07	0.06	0.09	-24.11
2	2	10	20	0.5	0.22	0.10	0.21	-18.12
3	2	15	25	0.6	0.37	0.30	0.36	-11.04
4	3	5	20	0.6	0.01	0.01	0.01	-40.40
5	3	10	25	0.4	0.03	0.02	0.05	-30.29
6	3	15	15	0.5	0.08	0.05	0.01	-32.60
7	4	5	25	0.5	0.07	0.07	0.19	-23.21
8	4	10	15	0.6	0.10	0.07	0.10	-22.39
9	4	15	20	0.4	0.08	0.08	0.10	-22.74
		Total			1.07	0.80	1.16	

Overall mean MRR ($\overline{MRR}$) = 0.11mg s^{-1}

Table 3 — Average values and Main effects: MRR (mg s^{-1})

Process parameter	Level	Tool dia. (A)		Flow rate (B)		Powder conc. (C)		Pressure (D)	
Type of data		S/N Ratio	Raw data	S/N Ratio	Raw data	S/N Ratio	Raw data	S/N Ratio	Raw data
Average values (% MRR)	L1	-17.75	0.20	-29.24	0.06	-26.37	0.07	-25.71	0.07
	L2	-34.43	0.035	-23.60	0.10	-27.08	0.09	-24.64	0.11
	L3	-22.78	0.09	-22.12	0.16	-21.51	0.16	-24.61	0.15
Main effects (%MRR)	L2-L1	-16.67	-0.16	5.63	0.04	-0.71	0.01	1.06	0.04
	L3-L2	11.65	0.06	1.47	0.05	5.57	0.07	0.03	0.03
Differences (L3-L2)-(L2-L1)		28.32	0.22	-4.15	0.01	6.28	0.05	-1.03	-0.01

Table 4 — Pooled ANOVA raw data and S/N data for MRR

Source	SS raw	SS S/N	SS' raw	SS' S/N	DOF raw	DOF S/N	V raw	V S/N	F-ratio raw	F-ratio S/N	P% raw	P% S/N
Tool Dia.	0.12	439.17	0.12	436.81	2	2	0.06	219.58	44.15	186.17	47.81	75.55
Flow rate	0.04	84.57	0.03	82.21	2	2	0.02	42.28	14.65	35.85	15.86	14.55
Powder conc.	0.04	55.14	0.03	52.78	2	2	0.02	27.57	14.18	23.37	15.35	9.48
Pressure	0.03	2.35	0.02	*	2	*	0.01	*	10.34	-	11.20	*
Error	0.02	2.35	0.03	9.43	18	2	0.001	1.17	-	-	9.74	0.40
Total	0.27	581.24	0.27	581.24	26	8	-	-	-	-	100	100

*Significant at 95% confidence level, F- critical=3.55 (Tabular value for raw data), SS- Sum of squares, DOF- Degree of freedom, V- variance , F- crirtical=19 (Tabular value for S/N data), SS'= Pure sum of squares, P= Probability of obtaining the observed results of a test.

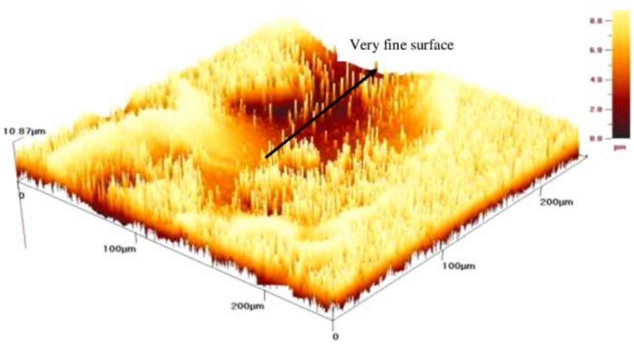

Fig. 6 —*Surface finish of machined workpiece measured by optical surface profilometer.*

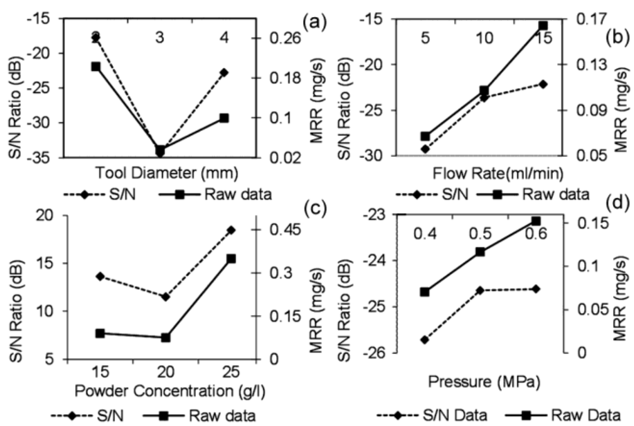

Fig. 7 — Effect of process parameters on MRR (mg s^{-1}).

The average values of MRR were calculated and plotted as shown in Fig. 7. It is clearly shown in Fig. 7 that parameters A, B, C, and D at levels 1, 3, 3, 3 respectively were most effective in increasing MRR. Similarly, signal to noise ratios was also calculated and display the same trend in Fig. 7. The parameter A at the 1st level, parameter B at 3rd level, parameter C at 3rd level, and parameter D at the 3rd level were most effective in increasing the MRR.

The exit area for the dielectric medium from thetool electrode tip at level 1 was low due to which the velocity of the dielectric coming out from the tooltip was very high as per the continuity law. The sparking was very vigorous at the inter-electrode gap due to this increased velocity of the medium along with the metallic powder. This nature of velocity of the dielectric medium enhanced the interaction of ions and molecules at the machining gap which resulted in a high value of MRR. The discharge velocity of the dielectric medium gets reduced on a further increase of tooltip areaat level 2, due to which the plasma reaction is not that significant and therefore the MRR gets reduced to the lowest value. The dielectric medium quantity at the machining gap increased on a further increase of tooltip diameter at L_3 due to which MRR again displayed an increasing trend as shown in Fig. 7.

The MRR tends to increase with the increase in the mist flow rate. High volume flow rate helps in faster flushing of debris and therefore results in faster erosion over the workpiece. The effect of metallic powder as an additive in the dielectric mist led to an increase in sparking frequency many times due to wide energized plasma which was obtained by the bridging effect of powder particles. The grains of powder particles interlock themselves which results in the formation of the bridge at the machining gap and they start behaving as the conductors. This phenomenon intensifies the electric field and the early explosion of sparks gets initiated. This phenomenon also reduces the insulating strength of the dielectric medium. The machining gap gets increased due to which the plasma channel also increases, therefore, more heat is transferred between the tool and workpiece electrodes which results in higher erosion rates. Similarly, the pressure of dielectric mist also showed the same trend on MRR. The flushing effect over the machined area was improved significantly due to which there was a phenomenon of effective quenching and a good degree of fluidity. High pressurized mist assisted in removing the debris from the crater efficiently which provided favorable conditions for flushing and enhancedrepetitive discrete discharge for an increase in MRR in machined products by PMND-EDM. The MRR was induced due to an increase in mist pressure because the dielectric mist (medium) was deionized sufficiently. MRR was higher at high mist pressure because the dielectric medium at high pressure and speed flow cools the machining area efficiently with better debris removal phenomenon from the solidified puddle of the workpiece. It was revealed that added metallic powders improve the breakdown characteristics of dielectric and hence machining rate increases but over powder concentration results in unstable discharges at the machining gapdue to short circuits at the inter-electrode gap. The interspace between the electrodes increased at a low range of powder concentration for electric discharge initiation and lowered the breakdown voltage. Therefore higher metallic powder concentration was not considered for experimentation.

3.2 Analysis of micro-hardness in machined parts by PMND-EDM.

Micro-hardness testing was performed on the surface machined by the PMND-EDM process. This micro-hardness measuring instrument utilizes a carbide indenter which indents with respect to an increase in the value of load applied. The graph was plotted between the depth of indentation (µm) and the load applied (mN). The micro-hardness testing was performed for all the machined samples for which the mean values are tabulated in Table 5. The output reading gave results for Vickers hardness number (HV) along with Young's modulus and Mohs hardness values. The maximum value of Vickers hardness number was 530.10 HV for the seventh sample machined by PMND-EDM as per Taguchi L_9 (OA). The graph plotted between the depth of indentation and force applied for the sample with maximum value for Vickers number is shown in Fig. 8. The conductive metallic powder in the dielectric medium is one of the reasons for the high value of Vickers hardness number. The additive such as metallic powder was responsible for changing the interaction between the conductors at the machining gap which results in topography change of the machined surface. The MH of the die steel workpiece was increased by adding chromium powder to the dielectric medium. An MH of 1600 HV was achieved with the addition of titanium powder to the dielectric.

Dielectric medium dispersion from the tool was found to be very suitable. Due to this proper dispersion, stable discharging was observed at the inter-electrode gap (IEG) which results in a higher value of MH. Secondly, the dielectric mist flow rate was most optimum in providing suitable normal discharges at the machining zone along with powder additives which results in a higher value of MH. The MH value increased with respect to increase in metallic powder concentration. As stated, the pyrolysis of dielectric results in diffusion of oxygen and carbon which also results in the formation of hard carbides and oxides over the top layer of the machined workpiece. All these factors resulted in achieving the enhancedmicro-hardness value at optimizedprocess parameter. Excellent debris removal and cooling effect over the machined sample at this mist pressure resulted in achieving the maximum micro-hardness value at the sample surface.

The surface modification influenced the micro-hardness value of the EN-31 machined samples. The

Table 5 — Micro hardness values for machined workpieces by PMND-EDM

Sample. No	HM (N/mm^2)	Young's modulus (GPa)	Vickers hardness Number (HV)
1	2049.92	174.71	234.44
2	3102.66	262.83	357.95
3	478.51	81.41	52.25
4	3007.32	224.34	353.69
5	3846.71	277.33	454.09
6	2667.68	109.04	331.05
7	4310.63	245.00	530.10
8	3731.26	132.84	503.23
9	2829.14	204.79	333.02

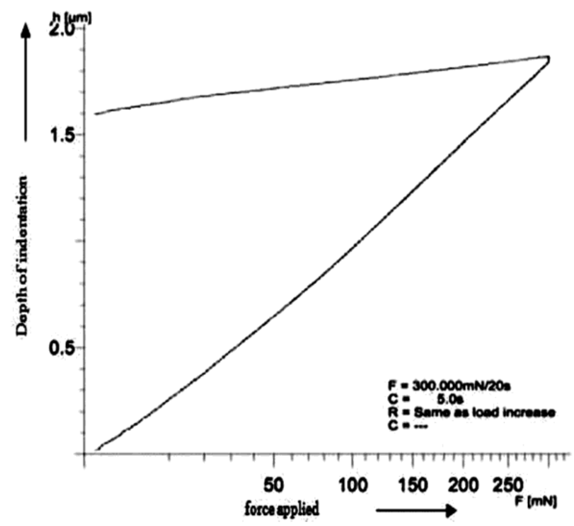

Fig. 8 — Depth of indentation Vs force applied for micro hardness testing.

micro-hardness value increased due to the formation of a solidified layer over the machined surface by the addition of metallic powder in the dielectric medium.

The hardness value for the seventh sample machined as per Taguchi L_9 (OA) was maximum because the concentration of metallic powder was maximum for the sample which resulted in the formation of a solid layer with a high value of Vickers hardness number. Micro-hardness of die steel work piece was increased by adding chromium powder in the dielectric medium. Metallic powder in the dielectric medium improved the topography of the work piece machined surface by reducing the size of pits and holes over the machined surface. The addition of conductive powder in dielectric medium improves the surface properties due to surface modification such as the formation of a solidified chromium layer. Factors such as type of metallic powder, current, gap voltage, and interaction between electrodes played a significant role in surface modification due to which the micro-hardness value increases to a higher value. Effect of addition of titanium powder to the dielectric was studied, this metallic powder as additive leads to the formation of titanium carbide layer with micro-hardness of 1600 HV on carbon steel when machined with the copper tool.

4 Conclusion

In this article, experimental investigations were conducted regarding the PMND-EDM process. The metallic powder (zinc) as an additive along with a mist of dielectric medium was used for performance enhancements. Further analysis of surface topography and micro-hardness was also performed and the following conclusions were drawn for the conducted research:

1 PMND-EDM process has been a hybrid method of machining that was efficient in machining rate.
2 The requirement of a large quantity of dielectric oil was eliminated as only a minute amount of dielectric oil was required for machining hard metals.
3 The metallic powder additives aided in the generation of a stable and more energized spark due to increased thermal conductivity at the inter-electrode gap.
4 The indigenously developed hybrid setup of PMND-EDM was efficient in terms of machining rate at optimized parametric values and better surface finish (1.1µm).
5 The MRR was found to be maximum at optimized experimental conditions. The optimum parametric experimental condition for maximum MRR was at A1, B3, C3, and D3. Therefore, tool diameter at A1 (2mm), a flow rate of mist at B3 (15 ml min^{-1}), the concentration of metallic powder at C3 (25 gm l^{-1}) and mist pressure of dielectric at D3 (0.6 MPa) were the most influential values which resulted in obtaining maximum MRR of 0.11 mg s^{-1}.
6 The predicted optimal range of material removal rate was 0.356 (mg s^{-1}) < MRR (mg s^{-1}) < 0.359 (mg s^{-1}).
7 Predicted mean of material removal rate at 95% confidence interval was 0.337 (mg s^{-1}) < MRR (mg s^{-1}) < 0.377 (mg s^{-1}).
8 It was concluded that the PMND-EDM method of machining at optimum input process parameters leads to the generation of machined parts with higher micro-hardness values.

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